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METALLURGICAL FAILURE ANALYSIS OF THE M230 MACHINE GUN BARREL – MIF-A-001-1999-I

Stacey Clark Kerwien
Robert Rocha

June 1999

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ARMAMENTS COMMAND
ARMAMENT RDE CENTER

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13. ABSTRACT
On 7 October 1998, an Apache Longbow Helicopter (AH-64D Longbow, 97-05031) crashed at Ft. Hood, Texas due to the rupture of the 30-mm M230 machine gun, which is attached to the front of the aircraft. The rupture was caused when the projectiles exited through the walls of the barrel, creating two holes approximately 20 to 23 in. up from the gun chamber.

The gun was removed from the helicopter and sent to TACOM-ARDEC for a metallurgical evaluation and failure analysis. Results from the evaluation show that the gun barrel had failed due to exposure to excessive heat. The change in the original steel microstructures from tempered martinensite to bainite and untempered martensite, coupled with the increase in steel hardness in the area where the projectiles exited, supports the theory that the steel had reached or exceeded the austenitizing temperature at the time of failure. This made the barrel very weak and allowed the projectiles to exit through the walls of the barrel.

14. SUBJECT TERMS
Steel alloy D6-AC Overheating Austenitizing Martensite Bainite Machine gun M230 Apache helicopter

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INTRODUCTION

On 7 October 1998, an Apache Longbow Helicopter (AH-64D Longbow, 97-05031) crashed at Ft. Hood, Texas due to the rupture of the 30-mm M230 machine gun, which is attached to the front of the aircraft.

During training exercises, the M230 was loaded with approximately 986 rounds of ammunition according to the crew, although the rounds counter was set to 1,000 rounds. Using the gun firing cycle as a guide, it was determined that before the malfunction occurred, 870 rounds were fired in 4 min 22 sec.[1] According to interviews conducted with the crew, the gunner stopped firing when he and the crew heard a change in the tone of the M230 gun.

After the crash site was investigated, the gun was removed from the helicopter and brought to the Armament Research, Development and Engineering Center (ARDEC), Picatinny Arsenal, New Jersey for a metallurgical investigation. The barrel had two holes in it and was severely deformed. The purpose of the investigation was to determine why the projectiles exited through the sidewalls, whether a projectile got stuck in the barrel, the barrel had overheated, or a flaw in either the gun or the ammunition had caused the malfunction.

EXPERIMENTAL PROCEDURE

First, a macroscopic inspection was performed on the gun and the gun was photographed in the "as-received" condition. An x-ray radiograph was performed by the quality Engineering Directorate, ARDEC to acquire information about the interior of the barrel before it was cut. Then, the barrel was cut longitudinally on a wire electric discharge machine (EDM).

One half of the longitudinally sectioned barrel was used for metallographic analyses while the other half was left intact. Sections of the barrel wall were cut, as shown in figure 1, then mounted and polished. Hardness measurements were performed using the diamond pyramid hardness (DPH) tester and then a semi-quantitative chemical analysis was performed on the specimens using energy dispersive spectroscopy (EDS). Finally, the samples were etched using nital to reveal the microstructures. Micrographs were taken of the microstructures using a light microscope/metallograph.

DISCUSSION OF RESULTS

Photographs

Figure 2 shows photographs of the barrel from the chamber end to just beyond the end of the remaining barrel support (or shroud). The barrel is severely deformed and there are two puncture holes that can be seen in the 0 deg view and the 180 deg view.

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[1]Memorandum from Sanford D. Breckons, CW5, dated 7 October 1988.

X-ray Radiography

In addition to the external features such as bulges, bends, and holes, the radiographic images revealed that the rifling had worn away 8.5 in. from the chamber end and did not reappear until 21 in. from the chamber end. In the area where there is no rifling, excessive bulging and deformation of the sidewalls is seen. The thickness of the sidewalls decreased in areas to half of its normal thickness. No evidence of porosity or cracks was noted.[2]

Macroscopic Examination of Longitudinally Cut Barrel

A photograph of the barrel after it had been cut along its entire length is shown in figure 3. In addition to the lack of rifling between 8.5 to 21 in. from the chamber end, yielding and deformation of the barrel material was noted, see arrows. At 10.5 in. from the chamber, the wall thickness dropped down to 0.30 in. where it is normally about 0.50 in.

The fracture surfaces at the holes, where the projectiles exited, were examined. The fracture surfaces were pointed and the material was elongated nearly 100%. No brittle fracture surfaces or tensile dimples were noted. Tensile dimples are seen when a material exceeds its room temperature tensile strength. This suggests that the material did not fail due to a void or other manufacturing defect but rather from overheating, which caused it to lose most of its tensile strength yet increased its plasticity properties.

There was no evidence of a projectile being stuck in-bore. The barrel was clean of any projectiles or fragments.

Semi-Quantitative Alloy Chemistry

The barrel steel was analyzed using EDS. Figure 4 shows the barrel chemistry next to the standard chemistry for D6-AC steel. This is an acceptable match for this test method.

Microstructure and Hardness

The microstructure and hardness in four areas of the barrel were examined to look for differences and changes to the original structure and hardness. The four areas analyzed were the muzzle end, through the large hole, a deformed area near the hole and the chamber end (fig. 1). Drawing no. 387-3116 calls out a maximum barrel hardness of 33 Rockwell C. Past work performed by the Failure Analysis Team at ARDEC has shown that the microstructure of the barrel is typically a tempered martensite (ref. 3).

Figures 5a through d were taken from the muzzle region. Figure 5a is the cross-section view, while figures 5b through d are microstructures from different areas of the cross-section.

---

[2]Memorandum from Emmett Barnes, U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ, dated 12 November 1998.

[3]Mortman, Mara, "Metallurgical Analysis of 30mm M230 Barrels, MIF A-6-94, U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ, 29 June 1994.

Figure 5b (50x mag., hardness 36 Rockwell C) was taken at a low magnification to show whether the microstructure in the lands and grooves had changed due to heat. No changes are seen. Figure 5c shows this same area at high magnification, 500x. This is a mixed microstructure and the hardness is a little high per the drawing.

Figure 5d (500x mag., hardness 30 Rockwell C) is the microstructure from the mid-wall of the muzzle region. This is a tempered martensite structure which is typical for the M230 barrel. The hardness is appropriate per the drawing.

Figure 6a is the cross-section view of the specimen taken from the large hole. Figure 6b (50x, 40 Rockwell C) is the microstructure of the lands and groove area at low magnification. This shows that, generally, some changes have occurred in the microstructure due to exposure to heat. Contrast figure 6b to figure 5b (from muzzle area) and it can be seen that figure 6b has more white areas than figure 5b. The hardness has also increased from 36 Rockwell C to 40 Rockwell C.

Figure 6c (500x, 53 Rockwell C) is the microstructure of the bullet exit hole. This microstructure contains bainite and untempered martensite. The presence of bainite and untempered martensite coupled with an increase in hardness from 30 to 36 Rockwell C to 53 Rockwell C can only be accomplished by heating the steel above its austenitizing temperature (~1,400°F) and then quenching. Not all areas of the gun barrel wall achieved temperatures as high or higher than 1,400°F. Some areas on the outer diameter only got warm enough to be further tempered, such as the area in figure 6d.

Figure 6d (500x, 27 Rockwell C) is a microstructure from the mid-wall. Compare it to figure 5d and contrast it to figure 6c. This structure is a coarse, tempered martensite. However, the hardness has dropped from 30 Rockwell C (as measured in the mid-wall of the muzzle) to 27 Rockwell C. For the hardness to drop as such, this area only got heated (or tempered) to about 1,200°F. This area did not go over the austenitizing temperature of 1,390°F and then get quenched.

Figure 6e shows the temperature profile of this area at the time of failure. At the exit hole and along the lands and grooves, the temperature exceeded 1,400°F. The mid-wall is shown reaching a temperature of 1,200°F while the outer diameter of the barrel stayed below a temperature of 1,200°F.

Figure 7a is the cross-section of the deformed area near the holes. This area got hot enough to yield but the projectiles did not exit through this area.

Figure 7b (50x, 54 Rockwell C) is a low magnification photograph of the lands and grooves area. The microstructure has changed due to heat in this area, as is evidenced by the presence of both the white and dark areas. Figure 7c is the same area at high magnification. Again, as in figure 6c where the hole was located, bainite and untempered martensite are observed. This area also, exceeded the austenitizing temperature and then was quenched in air to achieve this structure and hardness.

Figure 7d (500x, 34.5 Rockwell C) is the mid-wall area of the deformed area. This is a mixed microstructure and it is not clear what effect the heat had on this area.

Figure 8a is the cross-section of the chamber end of the barrel wall.

Figure 8b (50x, 40 Rockwell C) is the microstructure at low magnification showing no general changes to the microstructure due to overheating.

Figure 8c (500x, 33 Rockwell C) is the microstructure of the barrel mid-wall at the chamber end. This microstructure is fine tempered martensite. It is comparable to the microstructure seen in figure 5d from the mid-wall at the muzzle end. No changes in the microstructure due to overheating are seen. This is a proper microstructure and hardness for the D6-AC steel alloy used in the M230 gun barrel.

The change in the microstructures from tempered martensite to bainite and untempered martensite coupled with the increase in hardness values seen at the holes where the projectiles exited, supports the theory that the gun barrel steel exceeded the austenitizing temperature and then air cooled. A transformation temperature versus time (TTT) diagram is shown in figure 9. This diagram shows that the austenitizing temperature is 1390°F. The barrel may have gotten hotter than 1390°F, but with the various temperatures throughout the barrel and the subsequent variable quenching rates, it is difficult to pin down exactly how hot the barrel got in different areas.

Once the barrel steel exceeds the austenitizing temperature, the hot tensile strength plummets (fig. 10). This diagram shows that at 1200°F, the barrel steel has only 35% of the room temperature ultimate tensile strength. Room temperature strength values are given in table 1. Thus, at 1,200°F the yield strength of the steel is 40 ksi maximum with the chances being that the yield strength is actually far lower than that at the austenitizing temperature of 1,390°F.

CONCLUSIONS

During firing, the yield strength of the barrel decreased due to excessive heat. The temperature of the barrel exceeded its austenitizing temperature. The barrel distorted and bulged in the area 8.5 to 20 in. from the chamber end. This caused the ammunition to ballot. Excessive gas blow-by worsened the situation. Thus, when the projectile reached the point 21 in. from the chamber, where the barrel did not yield, it could not realign and continue down the barrel. At this point, the projectile exited through the barrel walls, which were very weak due to overheating.

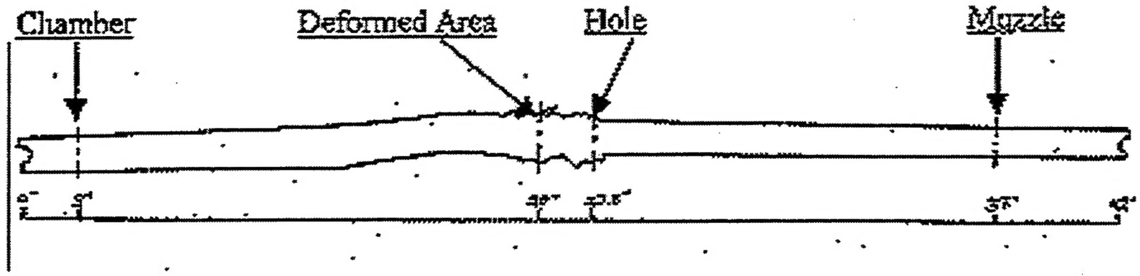


Figure 1
Outline of the failed barrel showing where metallurgical specimens were taken from

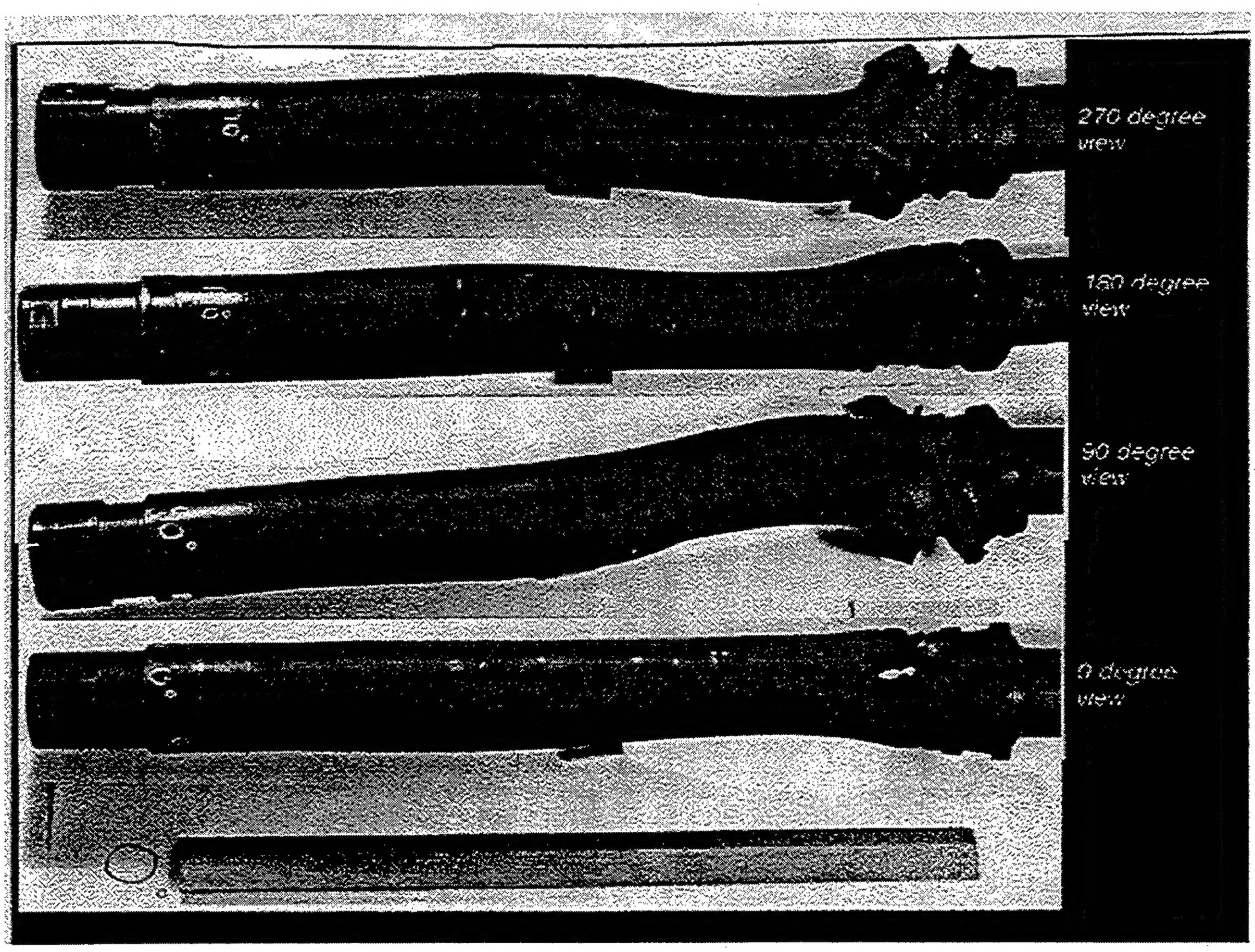
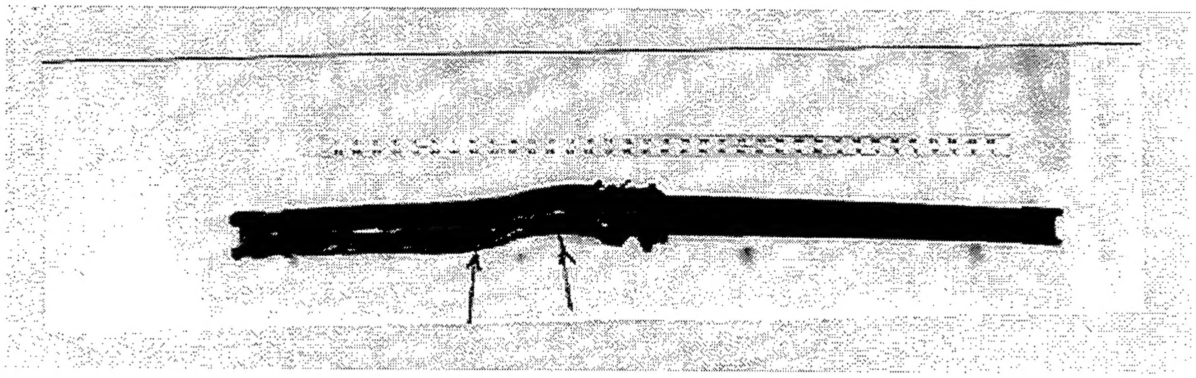


Figure 2
Chamber-end of the barrel, 360 deg view



Arrows point to areas where the material has yielded.

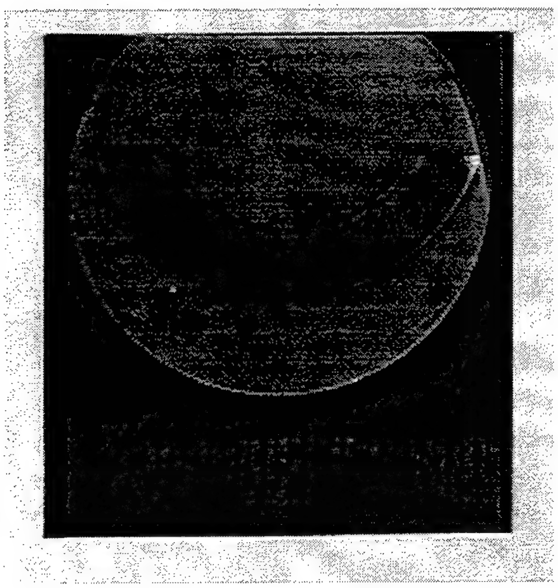
Figure 3
Sectioned M230 barrel

```
Sample /xd1/window1/#1,m230muzz.spt
Accelerating Voltage:             20.00 keV
Takeoff Angle:                    35.00 degrees
Library for system standards: /imix/spectra/system_standards.dir/20kev.dir
```

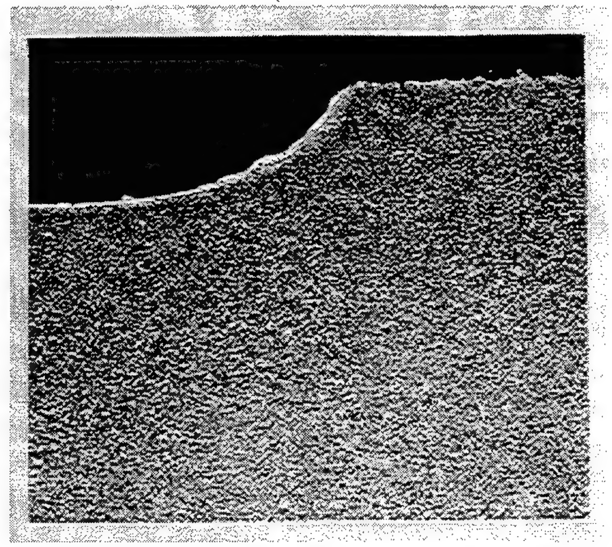
Elm	Rel. K	Norm wt%	D6-AC
Fe	0.9532	95.58	balance
Ni	0.0061	0.69	.4/.7
Cr	0.0129	0.99	.9/1.1
Mn	0.0090	0.92	.6/.9
Si	0.0021	0.41	.15/.30
V	0.0039	0.34	.05/.10
Mo	0.0080	1.07	.9/1.1
Total		100.00	

The standard alloy chemistry for D6-AC is shown for purposes of comparison.

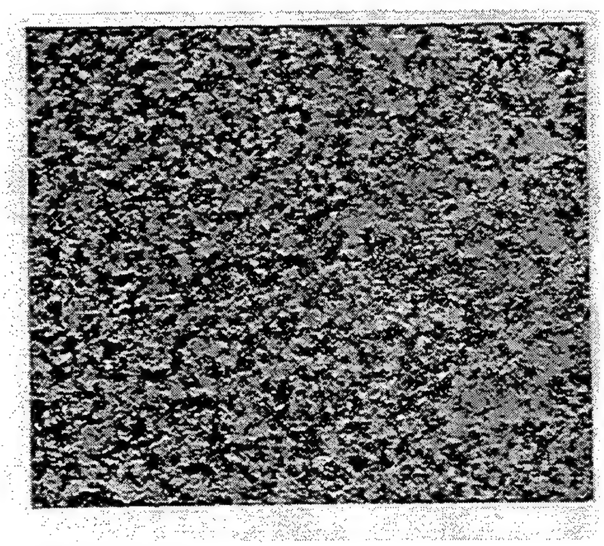
Figure 4
Semi-quantitative alloy chemistry of the M230 barrel



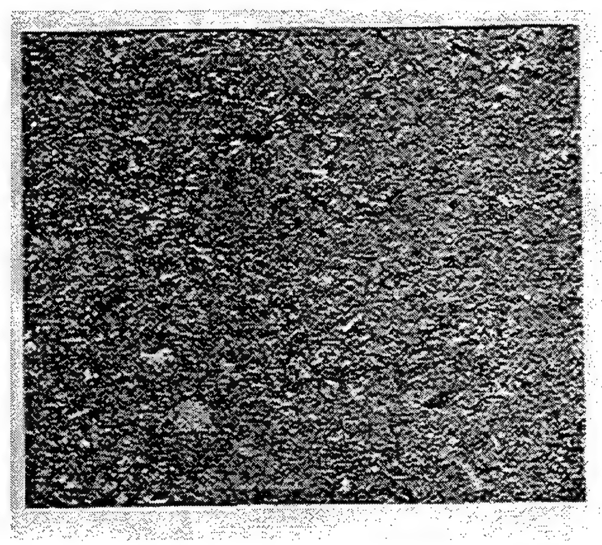
a
Cross-section of the muzzle area



b
Magnification, 42.6x

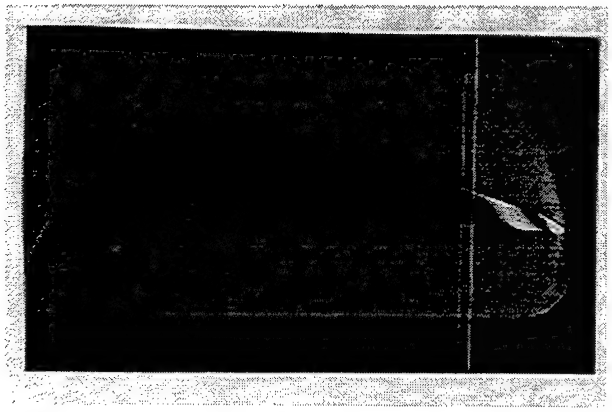


c
Magnification, 500x

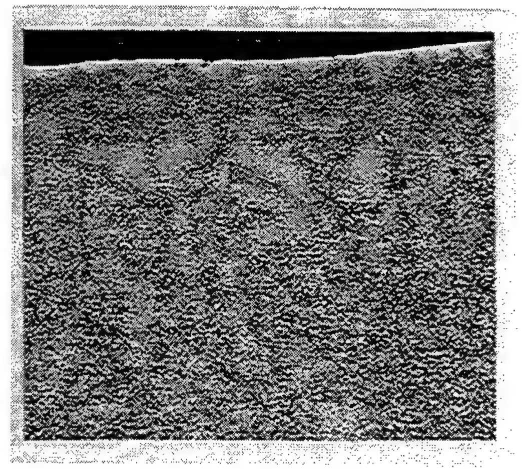


d
Magnification, 426x

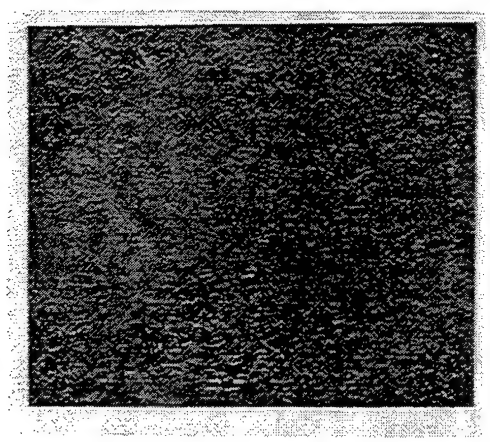
Figure 5
Microstructures of the barrel steel from the muzzle area



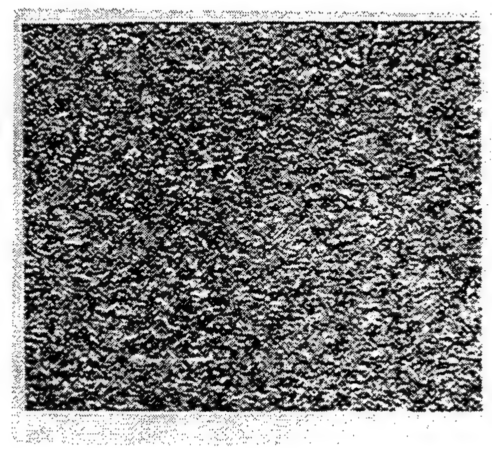
a
Cross-section of the hole region, 0.94x



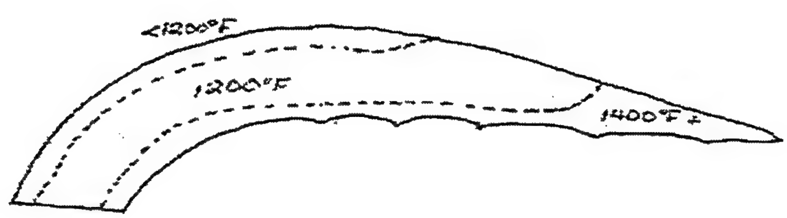
b
Magnification, 35x



c
Magnification, 350 x

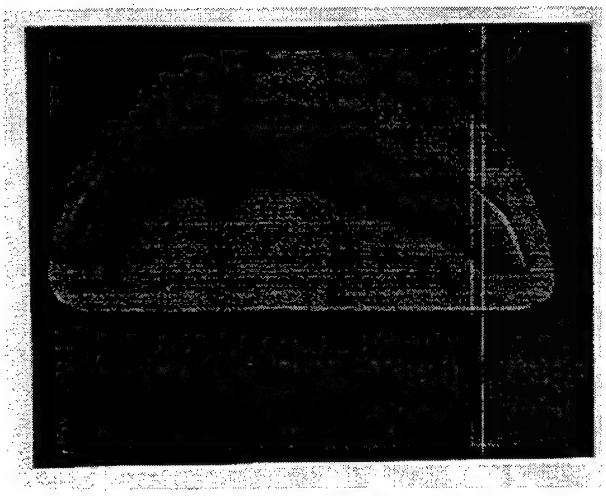


d
Magnification, 350x

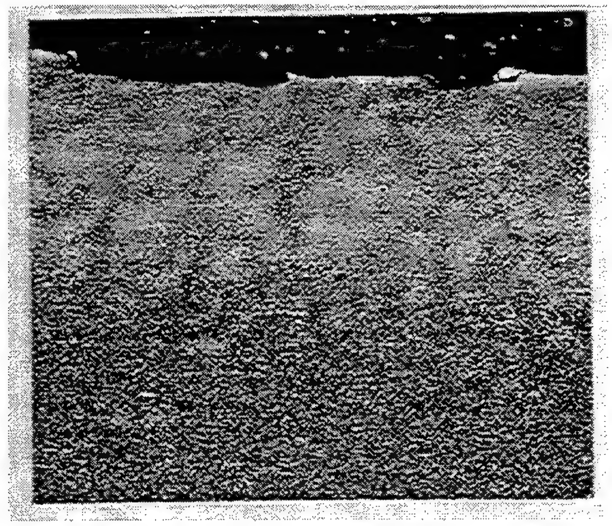


e
Temperature profile of the cross-section of the hole region at the time of failure

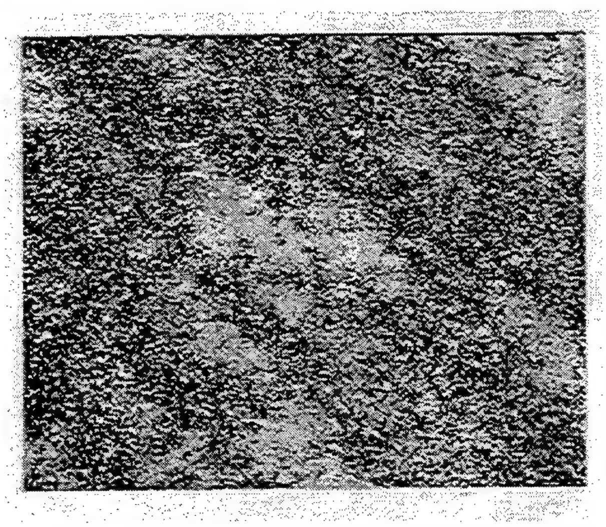
Figure 6
Microstructures of the barrel steel around the large hole



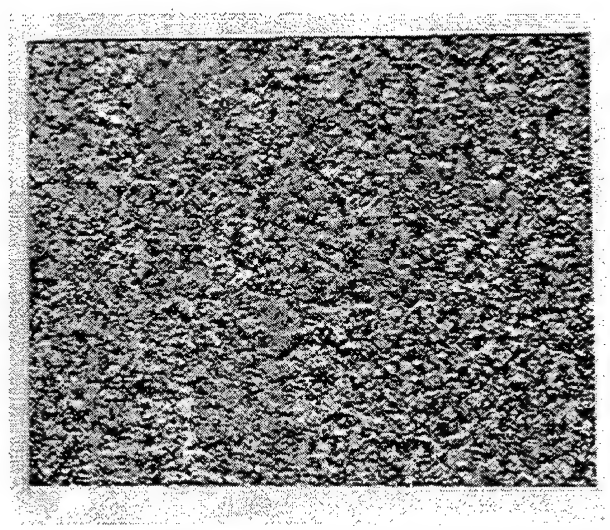
a
Cross-section of the deformed area



b
Magnification, 42.6x

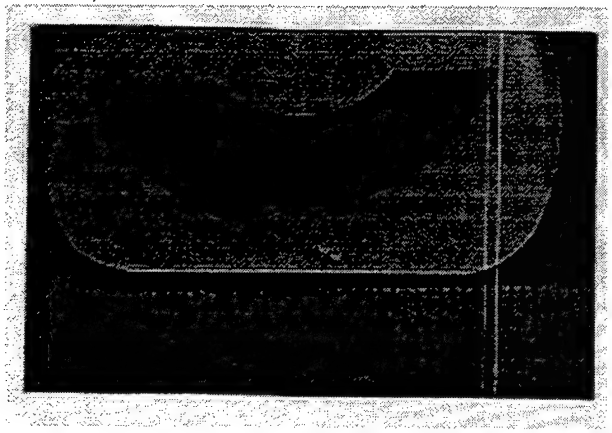


c
Magnification, 426x

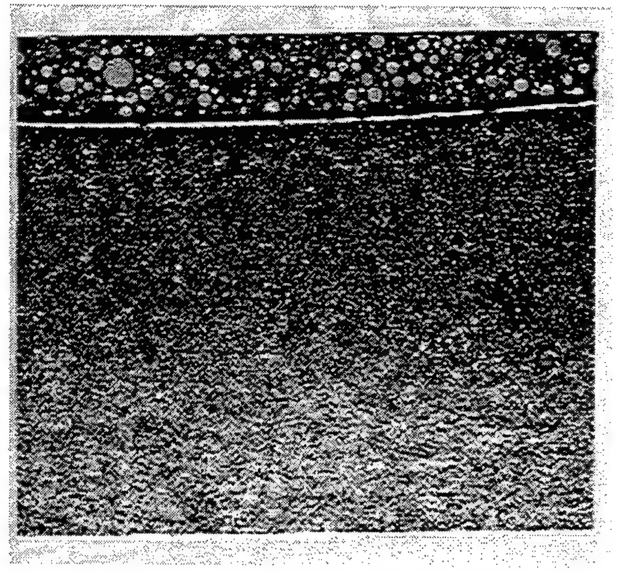


d
Magnification, 426x

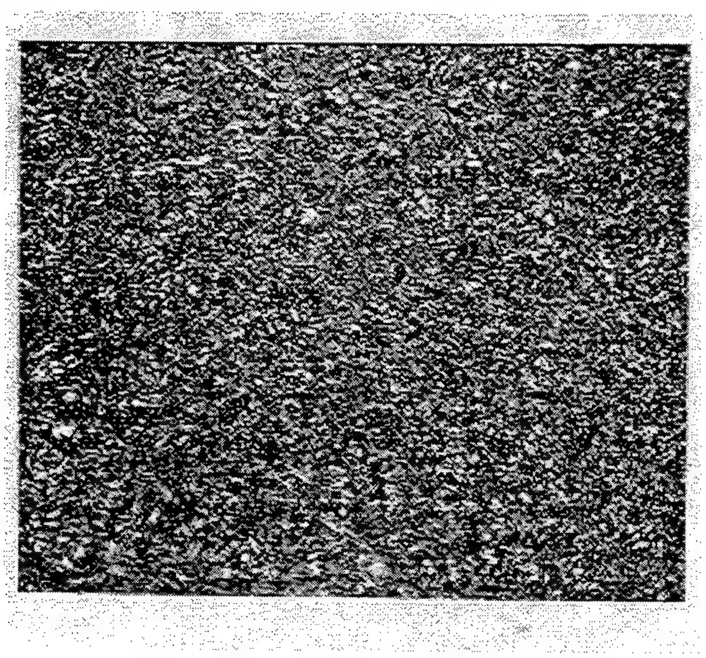
Figure 7
Microstructures of the barrel steel from the deformed area



a
Cross-section of the chamber area



b
Magnification, 42.6x



c
Magnification, 500x

Figure 8
Microstructures of the barrel steel from the chamber area

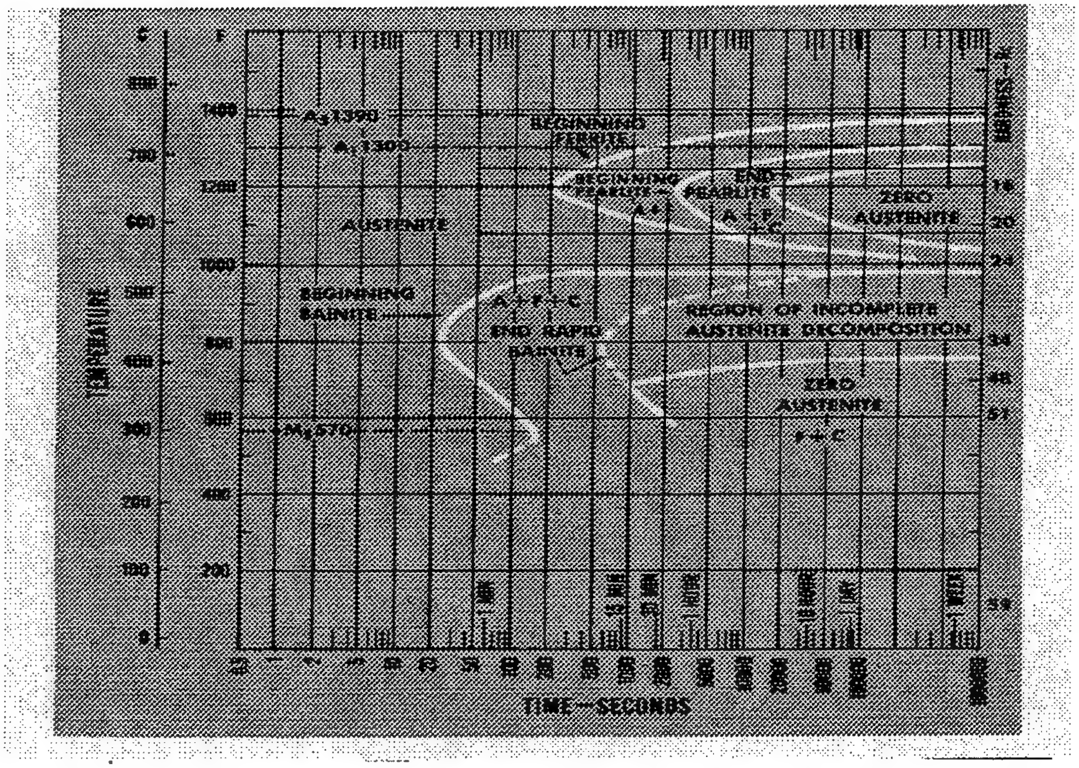


Figure 9
Transformation temperature versus time for medium carbon alloy steels[a]

[a]Republic Alloy Steels. Republic Steel Corporation, Cleveland, OH, p. 58, 1968.

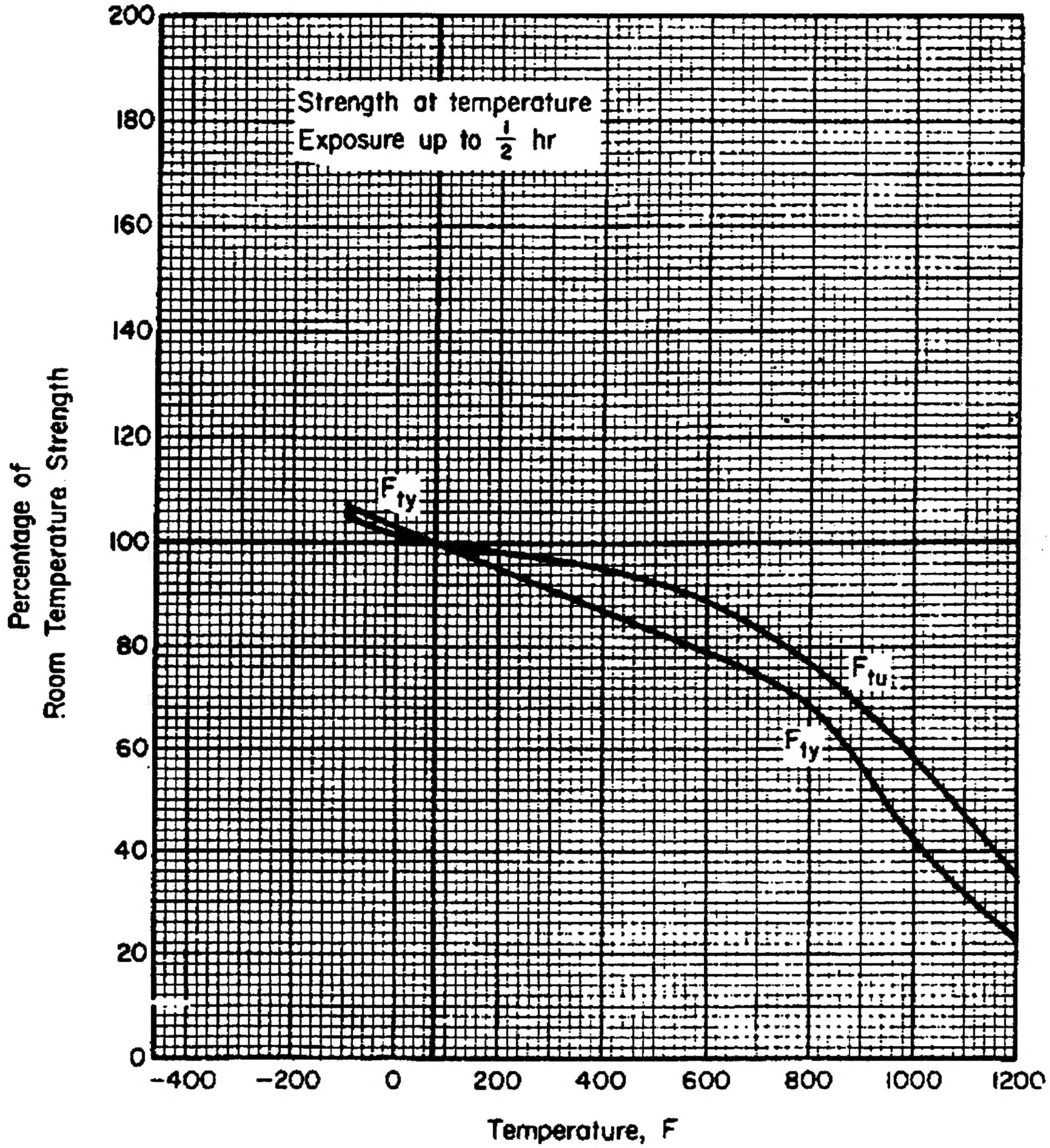


Figure 10
Effect of temperature on the tensile ultimate strength (F_{tu}) and tensile yield Strength (F_{ty}) of AISI low-alloy steels (all products)

Table 1
Mechanical properties of several alloy steels[b]

Alloy (For specification see Tables 2.3.1.0(a) and (b))	Hy-Tuf 4330V	D6AC 4335V	AISI 4340[b]	0.40C 300M	0.42C 300M
Form	All wrought forms		Bar, forging, tubing		
Condition	Quenched and tempered[a]		Quenched and tempered[a]		
Thickness or diameter, in.	See Table 2.3.0.2		See Table 2.3.0.2		
Basis	S	S	S[c]	S	S
Mechanical Properties:					
F_{tu}, ksi	220	220	260	270	280
F_{ty}, ksi	185	190	217	220	230
F_{cy}, ksi	193	198	235	236	247
F_{su}, ksi	132	132	156	162	168
F_{bru}, ksi:					
(e/D = 1.5)	297	297	347	414[d]	430[d]
(e/D = 2.0)	365	385	440	506[d]	525[d]
F_{bry}, ksi:					
(e/D = 1.5)	267	274	312	344[d]	360[d]
(e/D = 2.0)	294	302	346	379[d]	396[d]
e, percent:					
L	10	[e]	10	8	7
T	5[b]		—	—	—
E, 10^3 ksi	29.0				
E_c, 10^3 ksi	29.0				
G, 10^3 ksi	11.0				
μ	0.32				
Physical Properties:					
ω, lb/in.^{3}	0.283				
C, K, and α	See Figure 2.3.1.0				

[a] The use of heat treatments of F_{tu} ≥ 220 ksi or higher is subject to the specific approval of the procuring or certificating agency.
[b] Applicable to consumable-electrode vacuum-melted material only.
[c] Values in these columns are applicable only to steels for which the indicated F_{tu} has been substantiated through adequate quality-control inspection testing.
[d] Bearing values are "dry pin" values per Section 1.4.7.1.
[e] See Table 2.3.1.0(g) for elongation applicable to consumable-electrode vacuum-melted D6AC.

[b] MIL-HDBK-5F, pp. 2-17 and 2-19.

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